

Space-Grade, SWaP-Optimized, 10A, 150V, BLDC and Stepper Motor Control Platform Reference Design



Description

The TIDA-010984 presents a complete space-grade motor control platform. The design supports single 2- and 3-phase stepper or dual three-phase motor configurations with trapezoidal or field-oriented control (FOC), and scales across radiation hardness levels by pin-compatible components. MATLAB®/ Simulink® model-based design accelerates software development, while GaN technology and high device integration minimize board area and thermal overhead.

Resources

TIDA-010984, PMP23546

Design Folders

TPS7H6101-SEP, F28377D-SEP, INA901-SP

Product Folders

TMP9R00-SP, TPS7H5020-SEP, TPS7H5020-SP

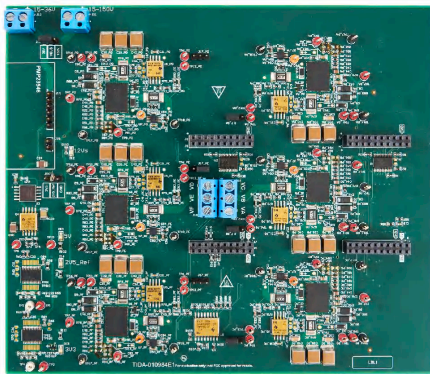
Product Folders

TL1431-SP, TPS7H1121-SEP, TPS7H1121-SP

Product Folders

TPS7A4501-SP, SN54SLC8T245-SEP

Product Folders



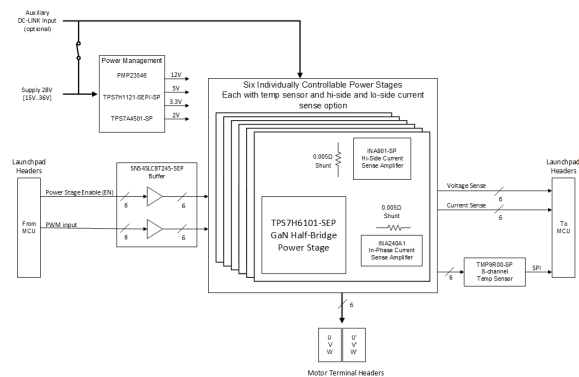
Top of Board

Features

- Supply voltage, DC-Link voltage: 22-36V, optional range: 15V – 150V
- Six individual shoot-through protected 10A, GaN half bridge power stages in support of:
 - 2x BLDC/PMSM
 - 2-phase stepper
 - 3-phase stepper
- High-side and in-phase current sensing option for each half-bridge power stage
- Individual temperature monitoring of each half-bridge power stage
- Demonstrates less than 60 cm² of board area required (single-side mounted)
- Connects to space-grade MCU F28377D-SEP running Matlab Simulink example for sensorless FOC
- Radiation hard and radiation tolerant mounting options

Applications

- Satellite motor and actuator drive electronics



Block Diagram

1 System Description

1.1 Terminology

- PWM - Pulse Width Modulation
- EMI - Electromagnetic Interference
- GaN - Gallium Nitride
- FET - Field Effect Transistor
- LDO - Low Dropout Regulator
- ADC - Analog to Digital Converter
- GPIO - General Purpose Input/Output
- BOM - Bill of Material

1.2 Key System Specifications

Table 1-1. Specifications

PARAMETER	SPECIFICATION
Input voltage	22V to 36V, 28V nominal
Max DC-link input with INA901-SP disconnected by unmounting zero-Ohm Resistors	limited by TPS7H6101-SEP
Power FET $R_{DS(on)}$ (defined by TPS7H6101-SEP)	Typ 16m Ω ($T_A = 25^\circ\text{C}$)
Power FET type	Rad hard GaN technology
Shunt resistance	5m Ω
Current measurement range	$\pm 17\text{A}$
Max phase current continuous (25C, no forced ventilation)	11A _{rms}
PWM control / frequency	Single PWM input / 20kHz
Automated PWM deadband configuration high-to-low / low-to-high	<53ns / <37ns
Point of load voltages	12V, 5V, 3.3V, 2V
Control I/F to MCU	3.3V CMOS TI BoosterPack compatible
PCB size	1320mm $\times$ 1780mm
PCB area per power stage, including DC-LINK capacitors, hi-side and in-phase current sense circuitry, and temperature sensor.	~37mm $\times$ ~42mm with all components on top side
PCB layer stack	Eight-layer, 1oz copper / 35 μm thickness

2 System Overview

This reference design is a highly flexible evaluation platform of Texas Instruments (TI)'s radiation tolerant and radiation hardened motor control solutions in support of several motor types and configurations such as dual three-phase motor control or a single 2-phase or 3-phase stepper implementation.

It is composed of the C2000 MCU Launchpad™ EVM [LAUNCHXL-F28379D](#) and a booster pack board with six independently controllable TPS7H6101-SEP radiation-tolerant 200V 10A GaN power stages, each complemented with high-side and in-phase current sensing option and dedicated temperature monitor. Further, the design includes generation of all required voltage rails of 12V, 5V, 3.3V and 2V from an unregulated 28V supply allowing for an input range from 22V up to 36V. The actual DC-Link voltage to the motor can be configured for an acceptable range of 15V to 150V max.

The control signals from the MCU follow the standard 3.3V logic level definition. The power stages expect 5V logic level inputs. Two [SN54SLC8T245-SEP](#) devices provide the necessary voltage level translation. Rad-tolerant [TPS7H1121-SEP](#) or rad-hard [TPS7H1121-SP](#) low dropout linear regulator (LDO) devices provide the 3.3V and 5V rails.

The radiation hardened [TMP9R00-SP](#) provides up to eight remote and one local temperature monitoring capability with high-accuracy. Six of the remote temperature monitors available are mounted next to each of the six power stages on the design. Rad-hard [TPS7A4501-SP](#) low dropout linear regulator (LDO) provides the 2V rail for the [TMP9R00-SP](#).

Six instances of the radiation hardened [INA901-SP](#) current-sense amplifier withstanding common-mode voltages from –15V to 65V provide a high-side current sensing option for each of the power stages.

For backwards compatibility with the commercial grade power stage evaluation module [BOOSTXL-3PHGANINIV](#) there is also a commercial grade in-phase current sense option based on [INA240A1](#) mounted for each power stage output. A direct replacement in space-grade was not available at the point in time of this design. [INA1H94-SEP/-SP](#) combined with [OPA4H199-SEP/-SP](#) or [OPA4H014-SEP](#) for common mode input voltages from -150V to +150V can be a good upgrade for usage in space.

[INA901-SP](#) and [INA240A1](#) are supplied by the same 3.3V supply mentioned above.

For the generation of the 12V rails, the design takes advantage of the reference design [PMP23546](#): 2.4W multi-output PSR flyback reference design for bias supplies.

This reference design uses [TPS7H5020-SEP](#) as a primary-side regulated (PSR) flyback converter. The input accepts a 22V to 36V range to generate a 12V bias referenced to primary ground and another 12V output that can be referenced to another return. In this use case for the TIDA-010984 both 12V outputs are referenced to the single common ground of this design. The rad-hard precision programmable reference [TL1431-SP](#) provides the required up-to-36V input regulator for the start-up supply. [PMP23546](#) offers greater than 5% output regulation across loading conditions and less than 1% ripple on each output.

All components chosen for the power tree and also for the power stages themselves are available in -SEP and -SP grade and can be swapped out to meet specific mission profiles.

The C2000 MCU Launchpad EVM [LAUNCHXL-F28379D](#) provides a great evaluation platform for all devices of the TMS320F2837x family, including the space-grade member, [F28377D-SEP](#), due to the software and pin-compatibility to each other.

The design was verified with the Matlab Simulink example [Sensorless Field-Oriented Control of PMSM](#) running a 3-phase synchronous permanent magnet servo motor with sinusoidal back EMF (Teknic M-2310P-LN-04K) orderable through TI's web page under [LVSERVOMTR Evaluation board | TI.com](#).

2.1 Block Diagram

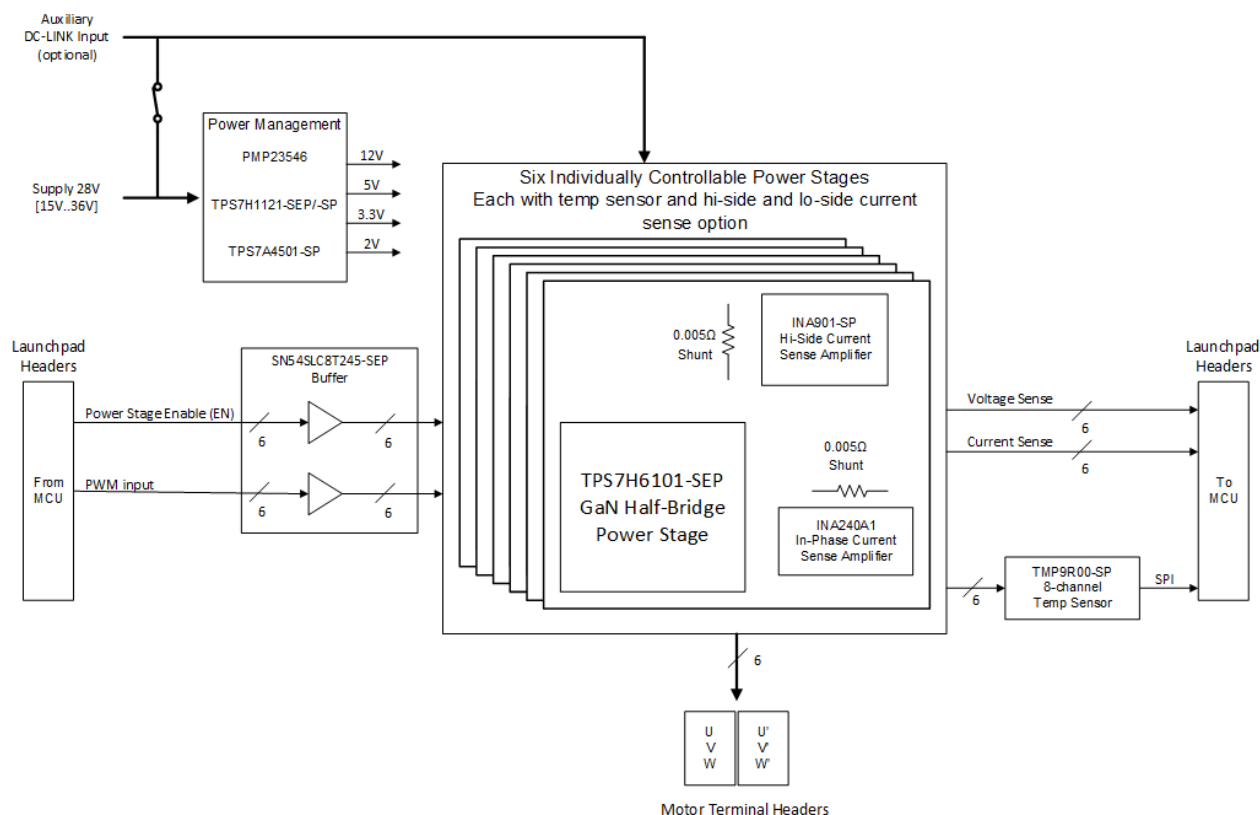


Figure 2-1. System Block Diagram of TIDA-010984

2.2 Design Considerations

2.2.1 Part Selection

A key consideration in component selection is scalability across mission radiation profiles. All the chosen power management devices have pin-to-pin compatible QML-P equivalents, which enables seamless scaling from lower radiation environments to higher radiation environments without board redesign or layout modifications. This strategy can help reduce development costs since a single PCB design can support multiple mission profiles. By maintaining electrical compatibility across the radiation tolerance range, this design can be rapidly adapted to meet different mission requirements while preserving the base architecture for reference.

2.2.2 Flexible Platform Approach

Six independent 200V rated power stages with high-side and in-phase current sensing options allow to scale across different motor types, DC-Link voltage levels and current sense techniques covering almost every motor and actuation in a satellite.

2.3 Highlighted Products

The following sections describe the highlighted products used in the reference design for the motor control MCU, power stage, current sense feedback, temperature monitoring and power management.

2.3.1 TPS7H6101-SEP

The TPS7H6101 is a radiation-tolerant 200V e-mode GaN power-FET half bridge with integrated grounds-up radiation hardened gate driver design. The same gate drive technology is also available as a family of discrete half-bridge drivers: TPS7H6003-SP, TPS7H6013 SP, TPS7H6023-SP, TPS7H6005-SP, TPS7H6015-SP, TPS7H6025-SP, TPS7H6005-SEP, TPS7H6015-SEP, TPS7H6025-SEP. This provides split output with high

source and sink current capability, dedicated hi-lo and lo-hi dead band configuration and low delay matching between hi- and lo-side switching for turn-on and turn-off switching behavior. Further, it demonstrates a very compelling SEE performance and is validated for zero cross conduction events up-to 75MeV×cm²/mg. With the TPS7H6101-SEP all these capabilities are available as a fully integrated half-bridge power stage with the power GaN FETs included that makes it very easy for designers to come to a highly optimized space-grade motor drive power stage design. The integration of the FETs naturally maintains the lowest possible traces between driver and FETs to minimize any parasitic impedances for switching characteristics. The slew rate and dead times are already resolved by the vendor to the greatest extent. The motor control power stage design discussed in this reference design does further take advantage of the single PWM control mode. Only a single PWM signal is provided to the power stage. The complement signal is generated inside the power stage device with adjustable dead times and the assurance that any issues in PWM signal generation cannot lead to a shoot through event. The implemented dead time follows TI's recommendation in the data sheet of the TPS7H6101-SEP.

The motor control use case of this reference design takes advantage of the TPS7H6101-SEP ability to handle switch node voltages as low as -10V.

2.3.2 F28377D-SEP

The TMS320F2837xD is a powerful 32-bit floating-point microcontroller unit (MCU) designed for advanced closed-loop control applications such as industrial motor drives; solar inverters and digital power; electrical vehicles and transportation; and sensing and signal processing. The MotorControl software development kit (SDK) for C2000™ MCUs accelerates application software development. The F2837xD supports a dual-core C28x architecture that significantly boosts system performance. Two so-called control law accelerators (CLA) enable highly deterministic execution timing of the control loop functions.

Performance analog and control peripherals are also integrated on the F2837xD MCU to further enable system consolidation. Four independent 16-bit ADCs provide precise and efficient management of multiple analog signals, which ultimately boosts system throughput. The Comparator Subsystem (CMPSS) with windowed comparators allows for protection of power stages when current limit conditions are exceeded or not met. Other analog and control peripherals include DACs, PWMs, eCAPs, eQEPs, and other peripherals.

2.3.3 INA901-SP

The INA901-SP is a voltage-output, current-sense amplifier that can sense drops across shunt resistors at common-mode voltages from -15V to 65V, independent of the supply voltage. The INA901-SP operates from a single 2.7V to 16V supply, drawing 700μA (typical) of supply current. The gain of the INA901-SP is 20V/V. The 130kHz bandwidth simplifies use in current-control loops. The pinouts readily enable filtering.

2.3.4 TMP9R00-SP

The TMP9R00-SP device is a radiation-hardened, multi-zone, high-accuracy, low-power temperature sensor using a two-wire, SMBus or I2C compatible interface. Up to eight remote and one local temperature zones can be monitored simultaneously. Advanced features such as series resistance cancellation, programmable ideality factor, temperature offset correction, and temperature limits are included to provide a thermal monitoring design. Each remote channel and the local channel have two independently programmable thresholds that trigger when the corresponding temperature exceeds the limit. A programmable hysteresis setting is available to avoid toggling around the threshold. The TMP9R00-SP device provides high accuracy (±1.5°C) and high resolution (0.0625°C) measurement capabilities. The actual temperature sensors positioned in close proximity to each of the power stage devices are implemented by small and cost effective BJT transistors in diode configuration. Application report [Remote Temperature Sensor Transistor Selection Guide](#) provides guidance for selecting the best suitable BJT and several space rated parts to choose from.

2.3.5 TPS7H502x-SP/SEP

The TPS7H502x is a radiation-hardened, current mode, single-ended PWM controller with integrated gate drivers. The TPS7H502x can be utilized in both silicon and gallium nitride (GaN) power semiconductor based converter designs. The controller integrates several key functions, such as soft-start, enable, and adjustable slope compensation while maintaining a small package size. The controller also features a 0.6V ±1% voltage reference tolerance to support highly accurate power converter designs. The driver stages for the controller have a wide input voltage range and supports peak source and sink currents up to 1.2A. The TPS7H502x has a

programmable regulator, VLDO, which can also be connected directly to the input of the driver stage (PVIN) to supply well-controlled gate voltage for operation with GaN FETs. The controller supports numerous power converter topologies, including flyback, forward, and boost.

2.3.6 TL1431-SP

The TL1431 is a radiation-hardened precision programmable reference with specified thermal stability over automotive, commercial, and military temperature ranges. The output voltage can be set to any value between $V_I(\text{ref})$ (approximately 2.5V) and 36V with two external resistors. This device has a typical output impedance of 0.2 Ω . Active output circuitry provides a very sharp turn-on characteristic, making the device an excellent replacement for Zener diodes and other types of references in applications such as onboard regulation, adjustable power supplies, and switching power supplies.

TPS7H502x-SP/SEP and TL1431-SP form the basis of the reference design [PMP23546](#): 2.4W multi-output PSR flyback reference design for bias supplies which generates the necessary 12V rails from the 28V unregulated supply voltage for this reference design TIDA-010984.

2.3.7 TPS7H1121-SP and TPS7H1121-SEP

The TPS7H1121-SEP/-SP is a radiation-hardened, low dropout linear regulator (LDO) which operates over a wide input voltage range and is optimized for powering devices in a space environment. The device is capable of sourcing up to 2A over a 2.25V to 14V input. The device offers excellent stability and features a programmable current limit with a wide adjustment range. To support the complex power requirements of FPGAs, DSPs, and microcontrollers, the TPS7H1121-SEP/-SP provides enable on and off functionality, programmable soft start, and a power good open-drain output.

2.3.8 TPS7A4501-SP

The TPS7A4501-SP is a low-dropout (LDO) optimized for fast-transient response. The 5962-1222402VHA can supply 750mA of output current with a dropout voltage of 300mV. The 5962R1222403VXC can supply 1.5A of output current with a dropout voltage of 320mV. Quiescent current is well controlled and does not rise in dropout, as with many other regulators.

2.3.9 SN54SLC8T245-SEP

The SN54SLC8T245-SEP device is an 8-bit non-inverting bus transceiver that resolves voltage level mismatch between devices operating at the latest voltage nodes (0.7V, 0.8V, and 0.9V) and devices operating at industry standard voltage nodes (1.8V, 2.5V, and 3.3V). The device operates by using two independent power-supply rails (VCCA and VCCB) that operate as low as 0.65V. This device is fully specified for partial-power-down applications using Ioff. The Ioff circuitry disables the outputs when the device is powered down. The VCC isolation feature is designed so that if either VCC input supply is below 100mV, all level shifter outputs are disabled and placed into a high-impedance state.

2.3.10 INA240A1

The in-phase current sensing circuitry based on the commercial-grade INA240A1 is carried forward from [BOOSTXL-3PHGANINV](#) to keep the space-grade power stage as close as possible to the parenting design configuration for easy board bring-up with minimal software changes.

Alternative space-grade in-phase current sensing designs from TI are available based on INA951-SEP or INA901-SP with a constant current source added to enable for bi-directional current sensing ([Bidirectional Topologies for the INA901-SP](#)), OPA4H199-SEP/-SP for up-to 40V common mode input voltage, or INA1H94-SEP/-SP combined with OPA4H199-SEP/-SP or OPA4H014-SEP for common mode input voltages from -150V to +150V.

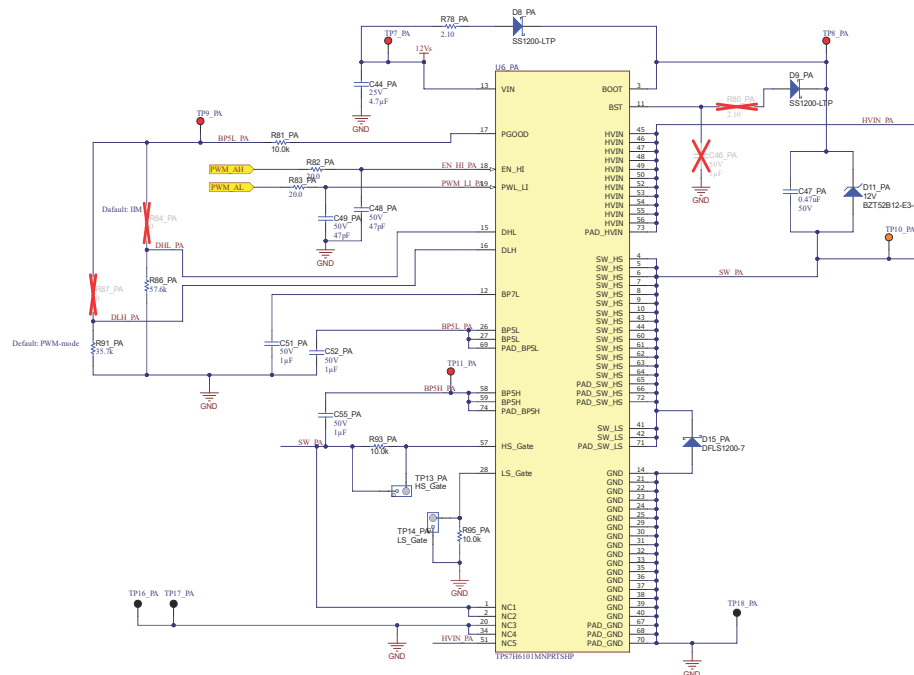
3 System Design Theory

3.1 Power Stage Design

Figure 3-1 shows the configuration of the TPS7H6101-SEP power stages.

With R87 and R84 not mounted, R91 set to 35.7kΩ, and R86 to 57.6kΩ the power stages are configured to operate in single PWM mode with internal deadtime generation with the values recommended in the datasheet for best performance. TPS7H6101-SEP grants two bootstrap charging options: direct charging from VIN and charging via the internal bootstrap switch. This reference design has provision for both options. Actual test results were taken with direct charging option. R78 and D8 are mounted, R80 and C46 are depopulated.

The only additional protection external to the power stage device is a Schottky diode between the FET source and drain pins. Unlike IGBTs or Silicon MOSFETs there is no reverse diode in a GaN FET. In case of a sudden power loss or an unexpected shut-off of both FETs of the power switch while there is still energy in motor this diode allows for a controlled path of the current without excessive peak voltages. Please note that in the design generated for this reference design the Schottky diodes have been only added for the low sides in support of test and debug ideas. For an actual product implementation it is recommended to add such diode to all the FETs.



3.2 Current Sense

The in-phase current sensing circuitry based on the commercial-grade INA240A1 is carried forward from BOOSTXL-3PHGANINV to keep the space-grade power stage as close as possible to the parenting design configuration for easy board bring-up with minimal software changes. A high-side current sense option based on INA901-SP is added as is typically used in stepper drives and in some cases also in three-phase motor applications for the benefit of a ground-fault detection capability (Figure 3-3). INA951-SEP is recommended if lower radiation hardness is required such as in LEO constellations.

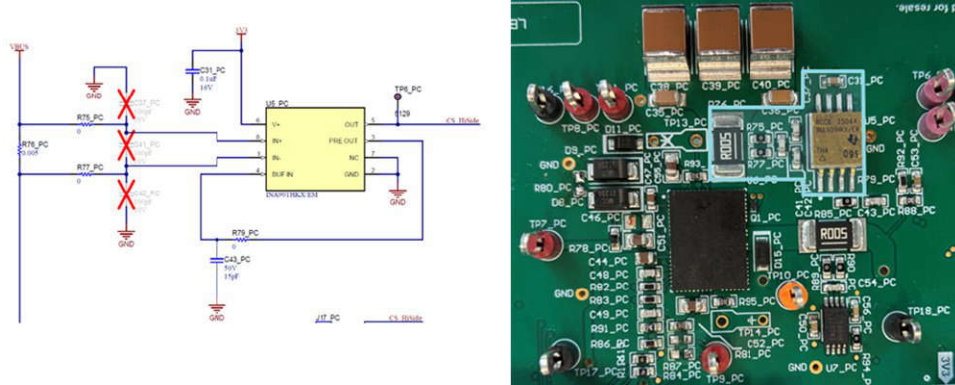


Figure 3-3. High-Side Current Sense Option Based on INA901-SP

Alternative space-grade in-phase current sensing designs from TI are available based on INA951-SEP or INA901-SP with a constant current source added ([Bidirectional Topologies for the INA901-SP](#), application note), OPA4H199 SEP/-SP for up-to 40V common mode input voltage, or INA1H94-SEP/-SP combined with OPA4H199-SEP/-SP or OPA4H014-SEP for common mode input voltages from -150V to +150V.

3.3 Temperature Monitoring

TMP9R00-SP enables the temperature monitoring of all six power stages from a single component. The actual temperature sensors positioned in close proximity to each of the power stage devices are implemented by small and cost effective BJT transistors in diode configuration. Excitation current generation, several signal conditioning features, voltage reference and analog-to-digital conversion are all integrated into TMP9R00-SP. Temperature values from all remote sensors and the local sensor inside the device are transferred to the MCU via I2C bus. Two programmable alarm signals THERM and THERM2 do also connect to the MCU GPIOs for interrupt generation.



Figure 3-4. Small and Cost Effective Implementation of Temperature Monitor with a BJT in Diode Configuration in Close Proximity to Each of the TPS7H6101-SEP Power Stage Devices

3.4 PCB Layer Stack

The design uses an eight-layer PCB with a rather low copper amount and thickness of 1oz and 35µm, respectively.

The top three layers are dedicated to the power stages based on TPS7H6101-SEP and high current carrying traces. The top layer carries almost all of the components. Very few components are mounted on the bottom side such as SN54SLC8T245-SEP and the corresponding passives for level shifting of the PWM control signals

and a few passives related to the temperature monitoring device TMP9R00-SP. No components are mounted on the bottom layer below the power stage circuitry.

Layer two (DC Link) and Layer three (GND) provide short return paths for any buffering capacitances in conjunction with the power stage (also referred to as bulk capacitance or DC-Link capacitance) and act as a shield to the layers below.

The layers four and five are embedded between the layer three, 3.3V supply plane, and the ground plane on layer six. Layer four and five are primarily used for the analog current sense and temperature monitoring signals that need good shielding from the expected switching noise from the power stages. The bottom layer is used for the digital control signals such as the PWM input to the power stage devices or the digital connection signals of TMP9R00-SP in horizontal routing direction. The top layer provides the corresponding vertical routing option for these signals, ideally in distance to the power stages to minimize the pick-up of the switching noise.

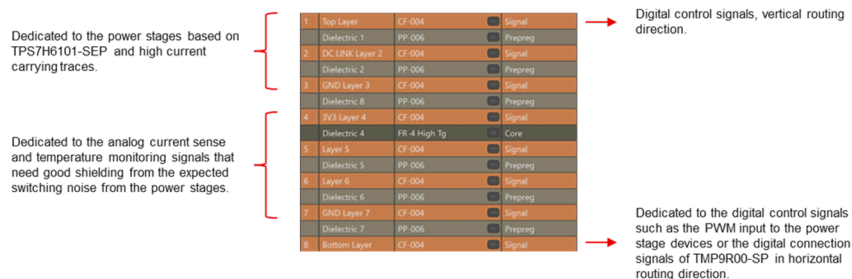


Figure 3-5. PCB Layer Stack

3.5 Optimizations or Trade-offs

The power stage design leaves further design optimizations in case improvements are needed in one or more of the following areas:

3.5.1 Board Area Savings and Component Count Reduction

1. The current sense circuitry except for the shunt resistor can be mounted to the bottom side. Only one current sense option, either high-side or in-phase is needed
2. Several passive configuration and filtering components can be mounted to the bottom side.
3. Only one of the bootstrap diodes is needed. The design provides both bootstrap options for evaluation purposes only.
4. The design provides a rather generous amount of bulk capacitance. This can likely be reduced in many applications. GaN FETs provide the advantage of greatly reduced switching losses over Silicon MOSFETs. An increase of PWM frequency can enable further reduction of bulk capacitance without significant increase in power loss or heat generation.

3.5.2 Signal Ringing / EMI Reduction

1. The high-side current sense option causes quite some distance between the bulk capacitances and the power stages. In-phase current sense option greatly helps to reduce this distance.
2. For the case of the in-phase current sensing option it is possible to further reduce the parasitic inductances in the power current path by mounting at least a portion of the bulk capacitors below the power stage device.

3.5.3 Heat Dissipation

1. Use of thicker copper layers, for example 2oz.
2. Further measures to *transport* the heat away from the power stage areas such as extra vias towards the bottom side of the PCB.

3.5.4 Cost

1. Reduction of layers. A four-layer PCB stack is sufficient.
2. Previously mentioned board area savings and component count reductions enable significantly smaller PCB and BOM cost.

3. Component mounting strictly on top side.

4 Hardware, Software, Testing Requirements, and Test Results

4.1 Hardware Requirements

- Power supply: rated to handle 35V or higher and 2A or higher for the motors described below
- Oscilloscope
- Current clamp
- Thermal imaging camera
- Motors:
 - Teknic M-2310P-LN-04K, 60V, 7.1A continued, 6000rpm, 4.6 V/krpm
 - Moons AC servo motor – SM0803DE2-KCF-NNV, 48V, 11.5A rated, 12.5A stall, 750W, 2.4Nm 3000rpm
- F28379D LaunchPad development kit for C2000™ Delfino MCU [LAUNCHXL-F28379D](#)

4.2 Software

4.2.1 Running the Matlab Simulink Model

The design is based on the commercially available hardware setup based on [LAUNCHXL-F28379D](#) , [BOOSTXL-3PHGANINV](#), and [LVSERVOMTR](#) (*application note*), fully supported by Mathworks' Simulink model-based implementation example of sensorless FOC available on the Mathworks web page: [Sensorless Field-Oriented Control of PMSM Using C2000 Processors - MATLAB & Simulink](#).

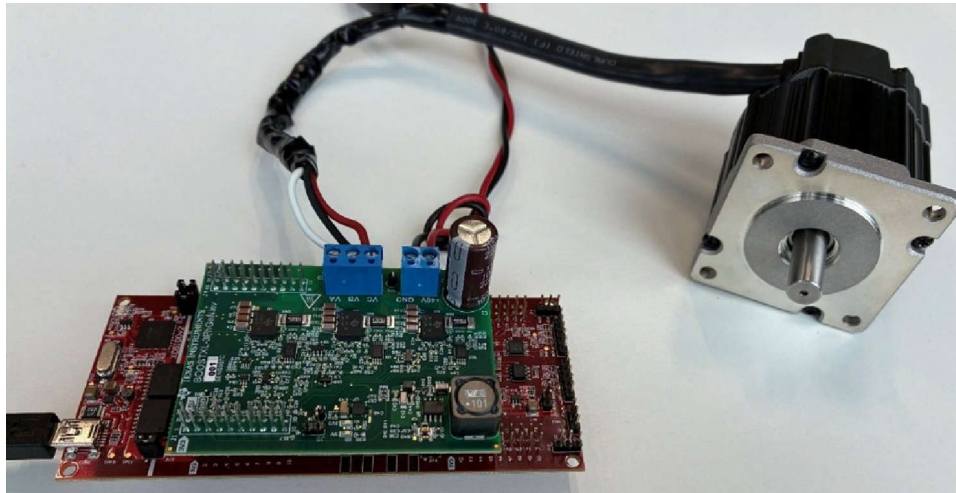


Figure 4-1. LAUNCHXL-F28379D, BOOSTXL-3PHGANINV, and LVSERVOMTR

It is recommended to get this setup and running first to verify the software installation and the proper configuration of the launchpad. Refer to this application note for assistance, [How to Run Matlab Simulink Motor Control Example on C2000 LaunchPad™ Development Kit](#).

4.2.2 Software Adaptations

The goal of the space-grade design is to take as much advantage as possible of this existing and well-proven setup. However, for robustness the TPS7H6101-SEP power stages are set to single PWM mode. Therefore, two modifications to the model are necessary.

TPS7H6101-SEP expects the single PWM signal on the *low-side* input PWM pin. The *hi-side* PWM input pin turns into a general enable pin for both of the FET drivers inside the device. This results into the need that the hi-side PWM signal in the original configuration for the [BOOSTXL-3PHGANINV](#) with two independent PWM signals per half-bridge power stage must be connected to the *low-side* connection for the space-grade design.

This can be easily done in the GUI of the Simulink model by clicking on each of the PWM blocks and selecting the option *Enable swap module A and B* and further disabling EPWMxA and enabling ePWMxB for each of the three PWM modules.

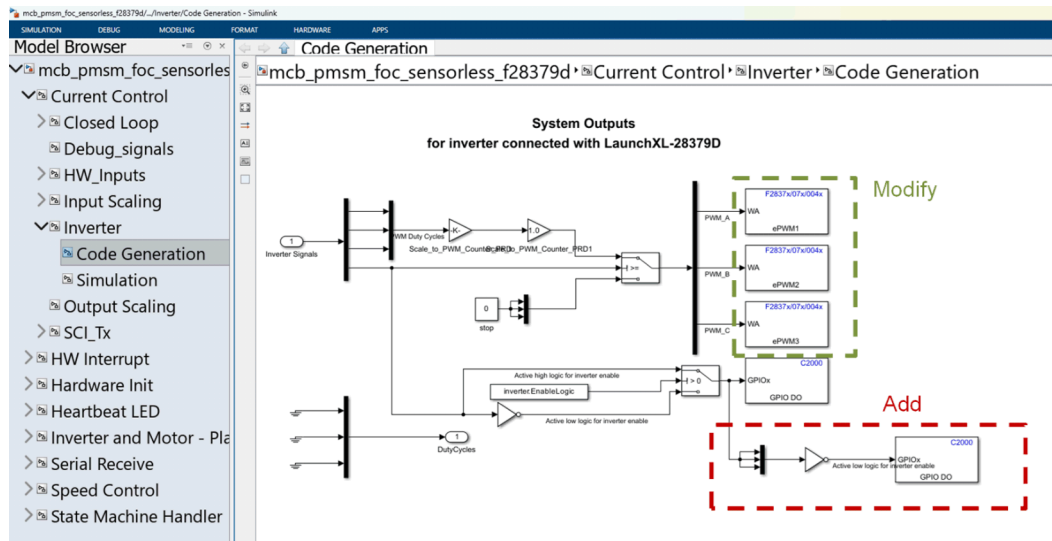


Figure 4-2. Modifications in the Simulink Model for Each of the PWM Blocks and the Addition of an Enable Signal for Each of the Power Stages

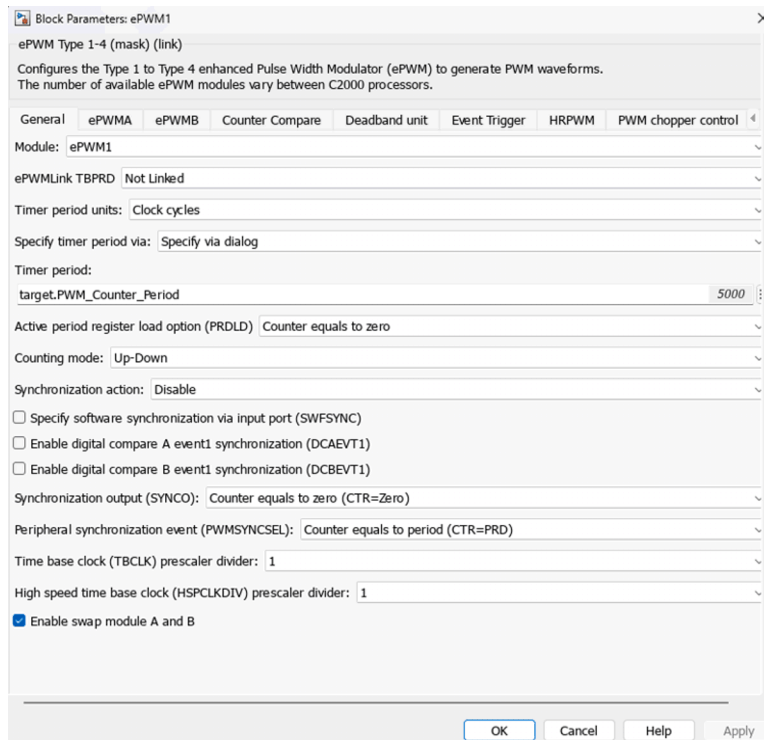


Figure 4-3. Inside the ePWM1 Dialog Box, General Tab: Enable swap module A and B Box Checked

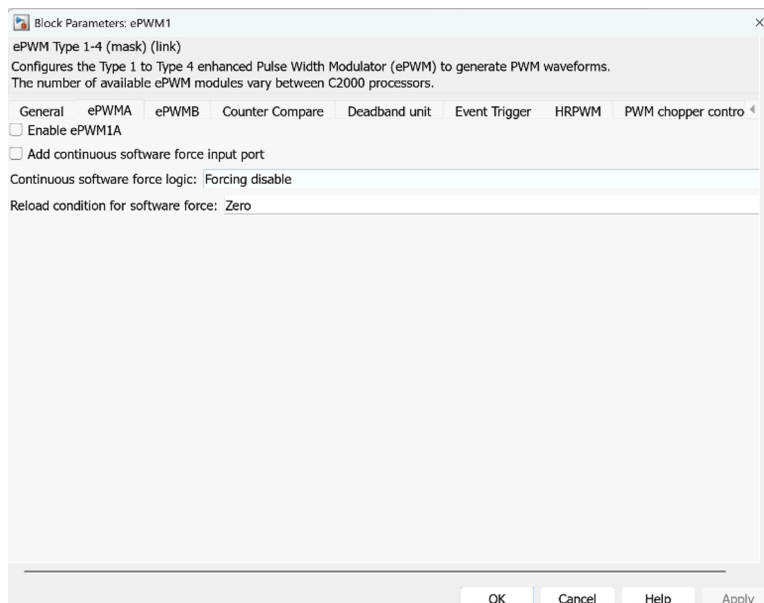


Figure 4-4. Inside the ePWM1 Dialog Box, ePWMA Tab: *Enable ePWM1A* Box Unchecked

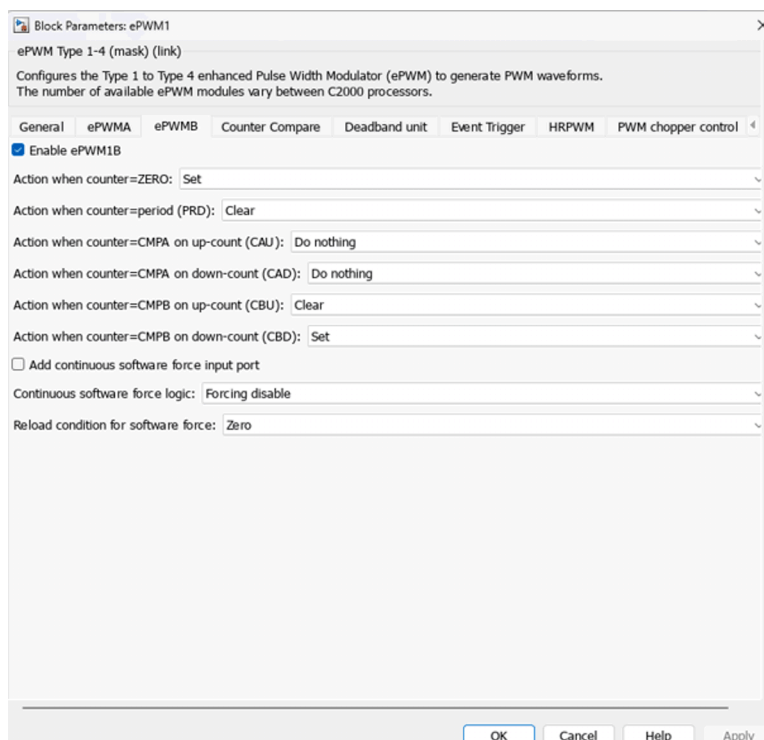


Figure 4-5. Inside the ePWM1 Dialog Box, ePWMB Tab: *Enable ePWM1B* Box Checked

For the enable signals for each of the power stage devices three additional GPIOs are activated together with the already implemented general inverter enable logic.

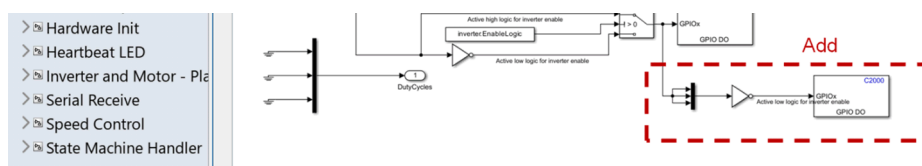


Figure 4-6. Three Additional GPIO Signals to Enable the Power Stage Devices TPS7H6101-SEP

Once the circuitry is added, double click on the new GPIO module and enable the GPIOs #0, #2 and #4.

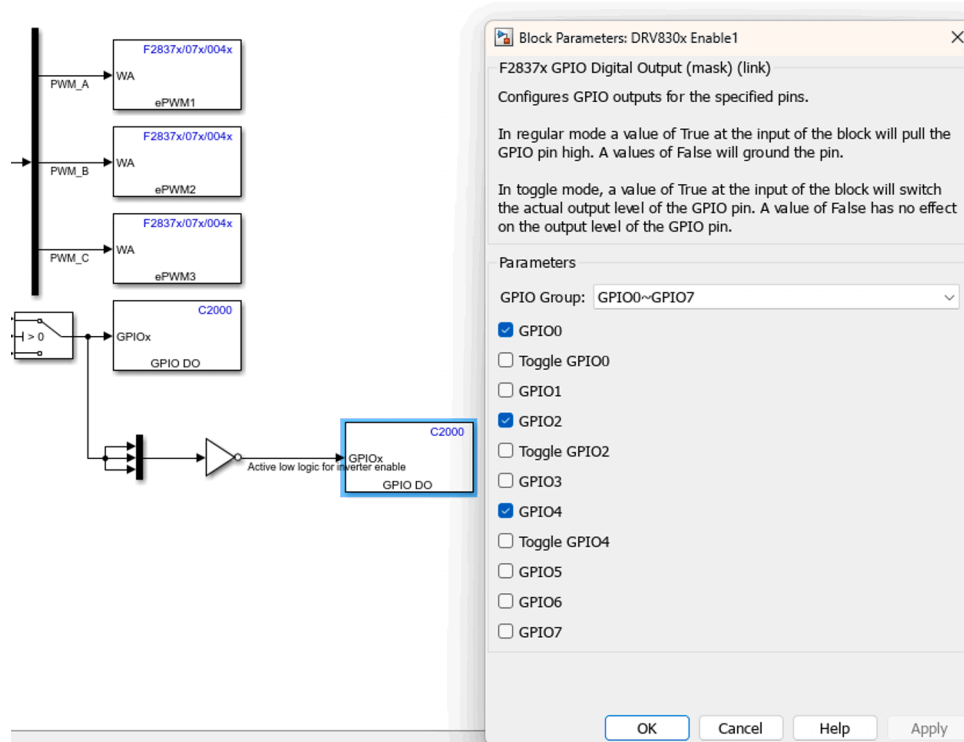


Figure 4-7. Check GPIO0, GPIO2 and GPIO4 to Activate Them as Enable Signals for The Respective Power Stage Device TPS7H6101-SEP

With these few changes applied the model can be compiled, built and loaded into the MCU. There is no need for changes to the host model.

4.3 Test Setup

4.4 Connecting the F28379D Launchpad

The F28379D Launchpad connects to the backside of the power stage PCB and is powered via the USB debugging interface to the PC with corresponding jumper headers mounted.

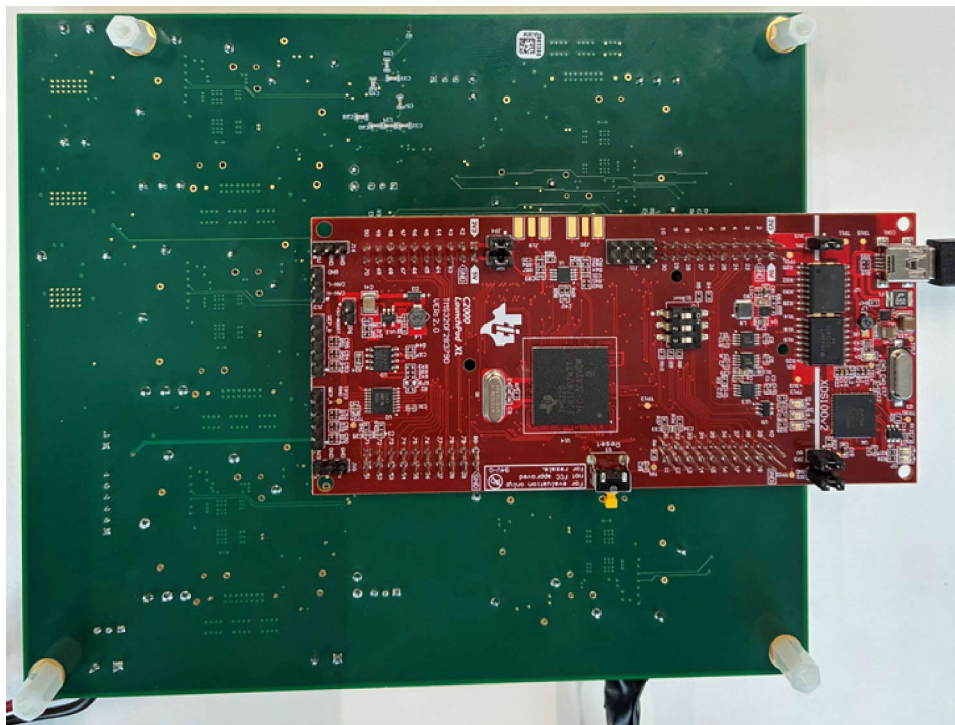


Figure 4-8. F28379D Launchpad Connects to the Backside of the Power Stage PCB

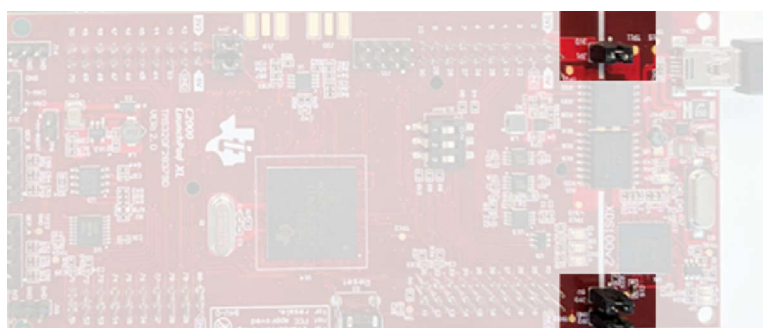


Figure 4-9. Apply Jumpers J1, J2 and J3 to Power the MCU Board Via USB Port, Independent of the Power Stage Board

Special care must be taken to connect the launchpad and the power stage boards together in the right orientation. The voltage and GND labels at the headers on each board provide good guidance.

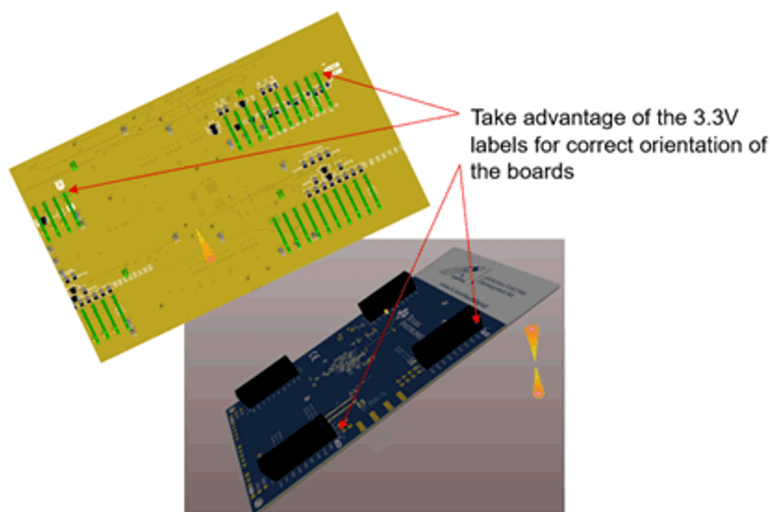


Figure 4-10. Connecting the Launchpad with the Power Stage Board in the Right Orientation

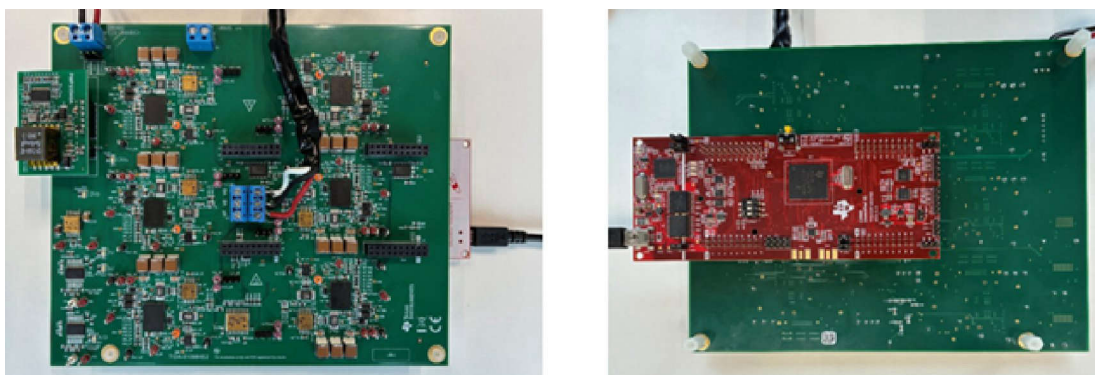
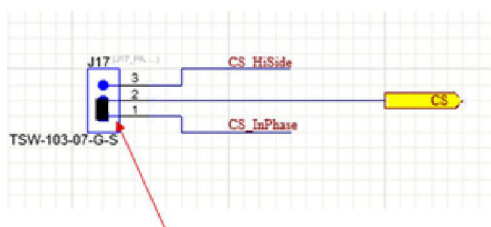
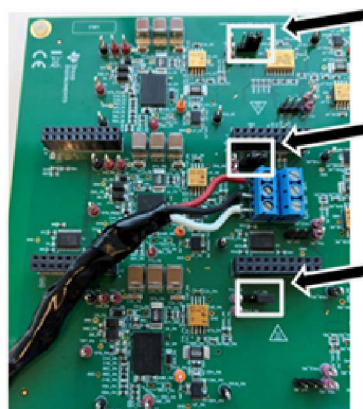


Figure 4-11. TIDA-010984 Power Stage Properly Mounted Onto the Launchpad Base Board

TIDA-010984 allows for selecting hi-side or in-phase current sensing option for each power stage individually.



Decide for each of the 6 phases for hi-side or in-phase current sensing and place the jumpers accordingly (example: in-phase current sense, compatibility mode to [BOOSTXL-3PHGANINV](#))



Jumper placement for in-phase current sensing for the power stages A, B and C

Figure 4-12. Jumper Placement for Current Sense Option Selection

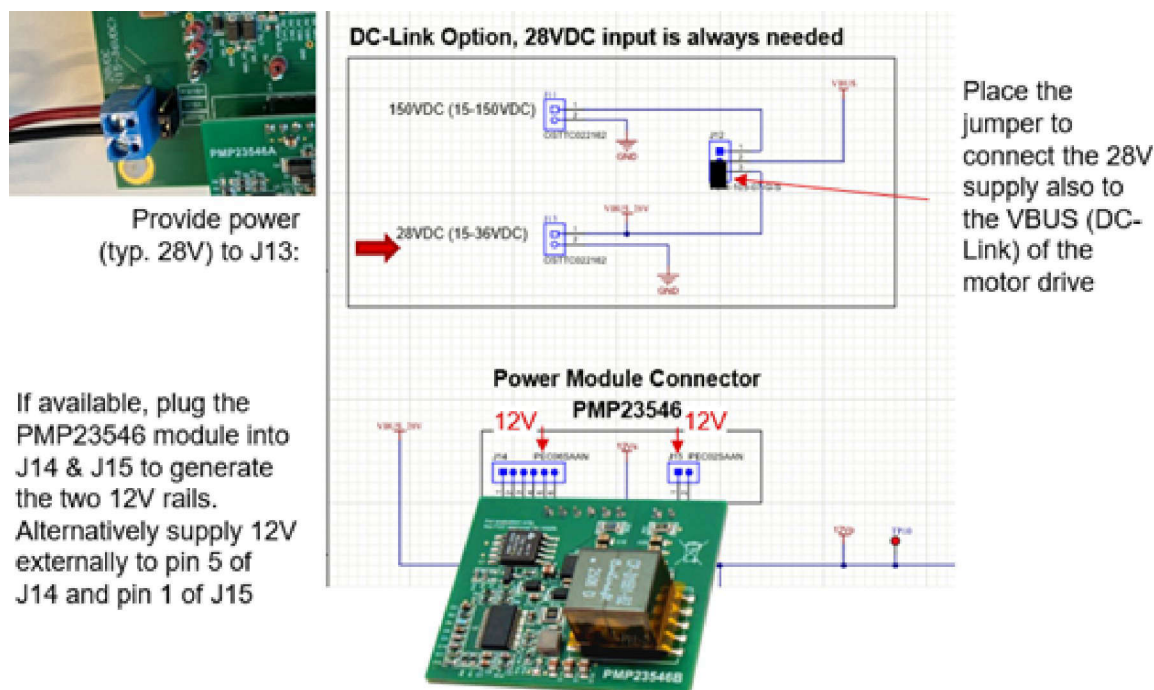


Figure 4-13. Supplying Power to TIDA-010984

The header connections to the two sets of power stages A, B, C and D, E, F are similar. This enables verification or comparison for any changes made at hardware or software level with very little overhead.

By shifting the Launchpad to the second set of the boosterpack headers the second set of the six power stages D, E and F, can be tested with the same single-motor software implementation intended to drive the power stages A, B and C in the standard setup without any changes.

4.5 Test Results

The software implementation runs in open loop for speed levels below 300rpm. For the following test results the DC-Link voltage is set to 28V and the speed to 100rpm (open loop), if not otherwise noted.

4.5.1 Dead Times

Figure 4-14 shows a representative waveform for turning off the high-side switch and enabling the low-side switch. The phase current corresponds to the output voltage of the INA240A1 current sensor. Note that the current sensor provides an inverted representation of the actual current into the motor phase since IN+ and IN- have been swapped in the design for optimized layout. The input for the current measurement signal into the oscilloscope has been inverted and its offset has been adjusted to show zero phase current at the central horizontal line. Figure 4-14 shows a small positive current into the motor. The dead time has been configured with an external resistor connected to RHL = 57.6kΩ as recommended in the data sheet. The observed 41ns is in line with the range of 36ns to 53ns with 44ns typical specified in the data sheet.

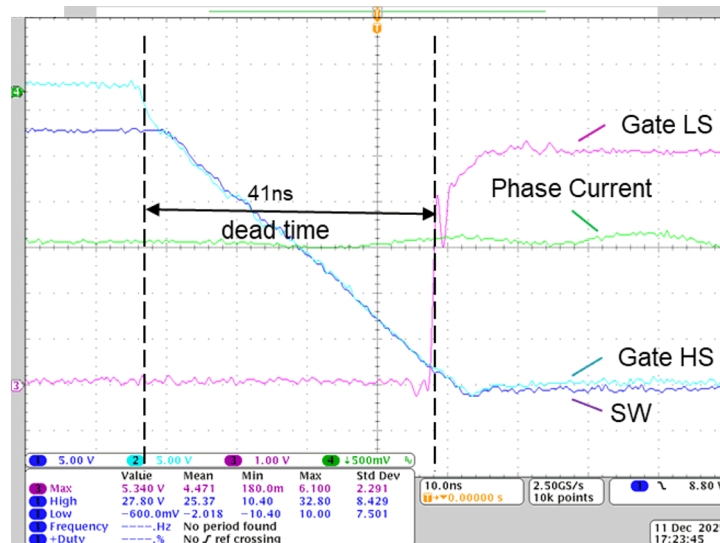


Figure 4-14. Dead Time Verification High-to-Low Transition

Figure 4-15 shows the opposite scenario with low-to-high switching. The dead time has been configured with an external resistor connected to $RLH = 35.7k\Omega$ as recommended in the data sheet. The observed 36ns is in line with the range of 20ns to 37ns with 30ns typical specified in the data sheet.

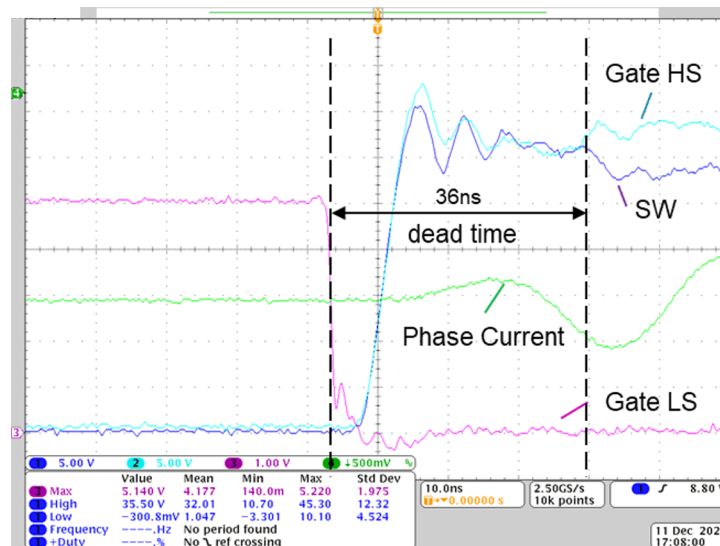


Figure 4-15. Dead Time Verification Low-to-High Transition

4.5.2 Ringing on Switch Node

The high-side current sense option causes quite some distance between the bulk capacitances and the power stages which results into quite some ringing on the switch node.

Worst case ringing with the highest amplitude happens for the case of low-to-high switching with a high positive current into the motor. While the device rating with 200V abs max maintains full reliability and also the low side gate stays well below the turn-on threshold, EMI can be a concern. [Section 3.5.2](#) provides recommendations for improvement.

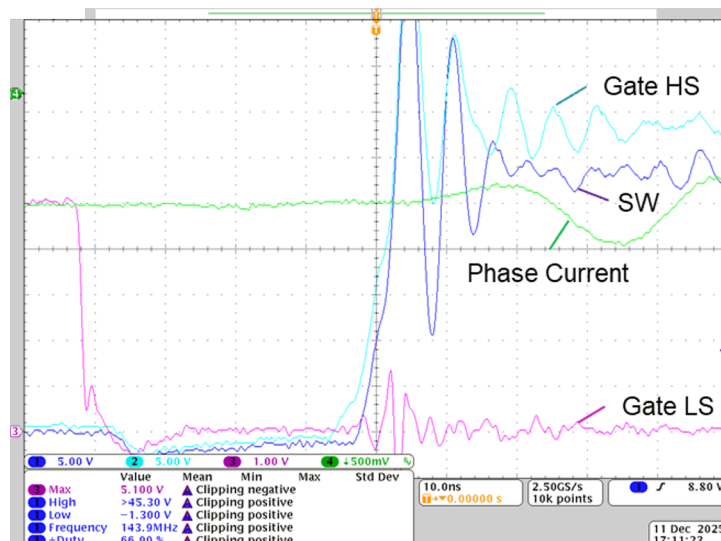


Figure 4-16. Worst Case Ringing for Low-to-High Switching with High Positive Current into the Motor

The highest negative amplitude of the switch node happens for the case of high-to-low switching with a high negative current into the motor. TPS7H6101-SEP provides -10V rating for the maximum negative voltage at the switch node. Figure 4-17 shows that the negative amplitude stays well within the specification.

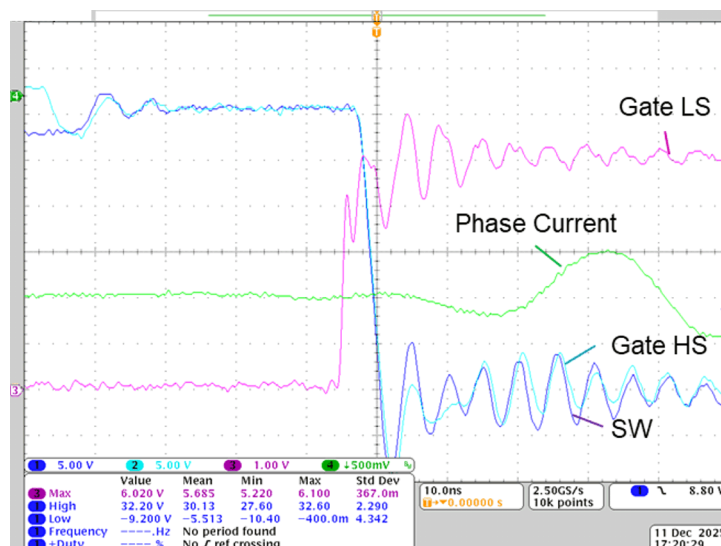


Figure 4-17. Highest Negative Amplitude of the Switch Node Happens for the Case of High-to-Low Switching with a High Negative Current

4.5.3 Thermal Images

Open loop motor control allows for injection of high currents into the motor despite the absence of any load.

Running the Teknic M-2310P-LN-04K motor at 100rpm in open loop with a DC-Link voltage of 28V causes a phase current of 4Arms. This can be measured with the help of a current clamp or by reading the INA240A1 current sensor output.

Figure 4-18 shows that at a continuous (>15min) 4Arms phase current there is only very little warming of the power stages under the condition of 24°C room temperature and no forced ventilation.



Figure 4-18. Heat Plot of the Power Stage Design at 4A_{rms} Phase Current Continuous (>15min)

For a stress test a more powerful motor with lower winding resistance was selected: Moons AC Servo Motor – SM0803DE2-KCF-NNV. By raising the DC-Link voltage to 33.1V at 50rpm (open loop) a phase current of 11A_{rms} got established. [Figure 4-19](#) shows the heat plot for 11A_{rms} continuous after 15min. Temperatures do rise as expected but stabilize below 120°C under the condition of 24°C room temperature and no forced ventilation.

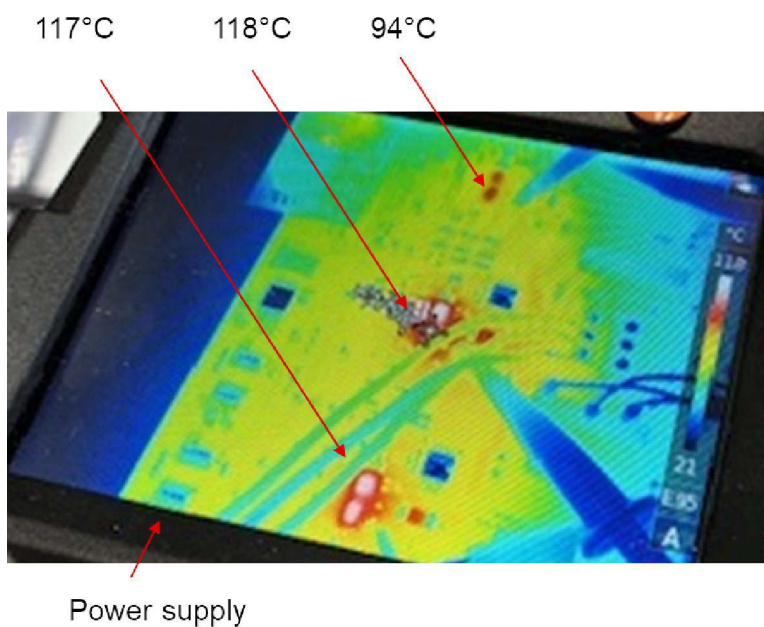


Figure 4-19. Heat Plot of the Power Stage Design at 11A_{rms} Phase Current Continuous (>15min)

5 Design and Documentation Support

5.1 Design Files

5.1.1 Schematics

To download the schematics, see the design files at [TIDA-010984](#).

5.1.2 BOM

To download the bill of materials (BOM), see the design files at [TIDA-010984](#).

5.1.3 PCB Layout Recommendations

For layout recommendations of the TPS7H6101-SEP refer to chapter 9.4 in its data sheet and [Section 3](#) of this document. Further, on general layout recommendations for GaN-based power stages in motor drive design please refer to the [TIDA-00909](#) design.

5.1.3.1 Layout Prints

To download the layer plots, see the design files at [TIDA-010984](#).

5.2 Tools and Software

5.2.1 Tools

- Texas Instruments, [LAUNCHXL-F28379D Development kit](#)
- Texas Instruments, [BOOSTXL-3PHGANINV Daughter card](#)

5.2.2 Software

Matlab Simulink example can be downloaded from MathWorks web page: [Sensorless Field-Oriented Control of PMSM](#)

Required MathWorks Products:

- Motor Control Blockset
- Embedded Coder
- Simulink Coder
- C2000 Microcontroller Blockset
- CCStudio™ IDE [Code Composer Studio version 20.0.1](#)

5.3 Documentation Support

1. Texas Instruments, [Highly Scalable Space Motor Control Platform based on TI's Space Enhanced Products \(-SEP\) and Space Products \(-SP\)](#) application note
2. Texas Instruments, [48-V, 10-A, High-Frequency PWM, 3-Phase GaN Inverter Reference Design for High-Speed Motor Drives](#) design guide
3. Texas Instruments, [48-V Three-Phase Inverter With Shunt-Based In-Line Motor Phase Current Sensing Reference Design](#) design guide
4. Texas Instruments, [LAUNCHXL-F28379D Overview](#) user's guide
5. Texas Instruments, [BOOSTXL-3PhGaNInv Evaluation Module](#) user's guide
6. Texas Instruments, [TPS7H6101-SEP 200V, 10A GaN Half Bridge Power Stage](#) data sheet
7. Texas Instruments, [TPS7H6101-SEP Evaluation Module](#), user's guide
8. Texas Instruments, [F28377D-SEP Dual-Core Real-Time Microcontroller](#) Data Sheet
9. Texas Instruments, [INA901-SP Radiation Hardened, -15-V to 65-V Common Mode, Unidirectional Current-Shunt Monitor](#) Data Sheet
10. Texas Instruments, [TMP9R00-SP 9-Channel \(8-Remote and 1-Local\), High-Accuracy Temperature Sensor](#) data sheet
11. Texas Instruments, [Remote Temperature Sensor Transistor Selection Guide](#) application report
12. Texas Instruments, [2.4W Multi-Output PSR Flyback Reference Design for Bias Supplies](#) test report
13. Texas Instruments, [TPS7H502x-SP/SEP and TPS7H503x-SP/SEP Radiation-Hardened Current Mode PWM Controllers With Integrated Gate Driver](#) data sheet

5.4 Support Resources

[TI E2E™ support forums](#) are an engineer's go-to source for fast, verified answers and design help — straight from the experts. Search existing answers or ask your own question to get the quick design help you need. Linked content is provided "AS IS" by the respective contributors. They do not constitute TI specifications and do not necessarily reflect TI's views; see TI's [Terms of Use](#).

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6 About the Author

MICHAEL SEIDL is a systems engineer in the Systems Engineering - Aerospace and Defense team at Texas Instruments.

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